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Evaluation of absorbed radiation dose on pregnant and fetus: Monte Carlo code

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Abstract

Aim: Our study focuses on the absorbance of ionising radiation of fetal organs as well as organs of pregnant women with the help of pregnant phantom female.
Materials and Methods: The measurement of radiation absorption during each trimester of pregnancy within head and thorax computed tomography (CT) was done. The study was designed to calculate radiation absorbance of pregnant woman and fetus through the head and thorax CT scan using Monte Carlo (MC) calculations. While we were calculating the ionizing radiation absorbance of fetal and maternal organs in each trimester, we also used two different shielding materials in the same thickness of 0.5 mm to see which one was more protective The study involved the maternal doses as well as fetal doses when the scan area excluded pelvic region.
Results: The absorbed fetal total radiation doses were 0.04 mGy,0.06mGy, and 0.08mGy, respectively. We added shielding of abdomen and received new values of absorbed fetal radiation doses for RPI- P3 pregnant female phantom; these were 0.0048 and 0.0076 after using the lead rubber and antimony-bismuth aprons, respectively. The shielding was very effective, and the lead rubber apron reduced the absorbed fetal radiation dose by approximately ten times. The lead rubber shielding was more protective than the antimony-bismuth.
Discussion: The absorbed radiation dose of fetal organs such as fetal brain beside maternal organs were underlined. The importance of shielding was explained using a comparative method, by showing the dose differences between the two materials. We concluded that lead rubber was providing more effective protection for fetus and mother visceral organs.

Keywords
Absorbed Dose; Computed Tomography; Monte Carlo; Pregnant; Fetus

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Introduction

During pregnancy, some common involvements considering medical problems or trauma could happen to pregnant women, and an emergent computed tomography (CT) would be required. In the literature, it is reported that a fetus will be exposed to 1 mGy of background radiation during pregnancy [1]. The fetal exposure to ionizing radiation depending on time and dose leads to a gestational age-associated occasion [2]. If extremely high-dose exposure (in excess of 1 Gy) occurs during early embryogenesis, it will be lethal to the embryo [2,3]. The ionising radiation such as 50-100mGy before implantation (0-2 weeks after fertilization) causes the death of an embryo or nothing (all or none). In organogenesis, that is 2-8 weeks after fertilization the critical doses of radiation may cause congenital anomalies and growth restriction. The data were based on results of animal studies, epidemiologic studies of survivors of the atomic bombings in Japan, and studies of groups exposed to radiation for medical reasons such as radiation therapy. It was reported that the intellectual disability and microcephaly malformations happened during 8-15 weeks that is the period of rapid neural development and migration. In humans, growth restriction, microcephaly, and intellectual disability are the most common adverse effects of high-dose radiation exposure [4]. It has been mentioned that an adverse effect may occur between 60–310 mGy [5,6].

Fetal risk of anomalies, growth restriction, or abortion has not occurred with radiation exposure of less than 50 mGy, a level that is far above for diagnostic procedures [7]. The risk of carcinogenesis as a result of in-utero exposure to ionizing radiation is unclear. A 10–20 mGy fetal exposure may increase the risk of leukemia by a rate of approximately 1 in 3,000 [5, 8]. CT is a standard imaging method, especially its usage has been increased by 25% per year 1997 to 2006 [9]. A pregnant woman may require CT angiography or head CT in the case of suspected pulmonary embolism or trauma, respectively. The radiation dose depends on mAs (milliamperage seconds), kV (kilovoltage peak), and pitch, so with regulations, the ionizing radiation can be reduced by approximately 2.5 mGy (including fetal gonad exposure) from 50 mGy [1]. Regular CT doses are variable [10]. In our study, we applied Monte Carlo (MC) calculations to determine the radiation dose absorbed in the pregnant female phantoms during head and chest CT. It is a technique used to understand the impact of risk and uncertainty in prediction and forecasting models. The last words were about the contribution of shielding and naming of the best protective shield material [11].

Material and Methods

The Pregnant Female Models

This study was approved by the local ethics committee. The pregnant female models developed at the Rensselaer Polytechnic Institute (RPI) were used [12,13]. The organ models were created by each voxel and boundaries of organs consisted of polygonal meshes or Non-Uniform Rational B-Splines (NURBS). Individual organs and fetal models were integrated into the adult female whole body according to gestation-related positions (Figure 1). For each organ, the volume and mass were specified manually according to reference values recommended in ICRP 103 [14]. Once all the organs and total body weights had been adjusted, the surface models were voxelized for dose calculations using the EGS4 MC code [15].

The MC model could simulate an actual Helical CT scan using different parameters. In our study, the simulation program was designed to apply the usual CT doses on a standard voxelized pregnant phantom then the absorbed dose in each body organ was measured using the mathematical models of the scanner, phantom, and specified scan parameters. Monte Carlo N- Particle (MCNPX) is a general-purpose MC radiation transport code. All radiation transport and dose calculations were performed using the MCNPX MC code [16]. Tally of the MCNPX was recorded at specific voxel locations corresponding to the metal–oxide–semiconductor field-effect transistor (MOSFET) physical measurements. Simulations of air scans were performed to obtain normalization factors to convert results to absolute dose values. Saturated organ doses have been reckoned by each organ with shielding has been measured, according to the results, each organ dose reduced with this strategy. The outcomes demonstrate that absorbed dose changes occurred depending on shielding material content.

The CT scanner model was GE LightSpeed Pro 16 (General Electric Healthcare Corporation, Waukesha, WI) for the MCNPX simulation. The CT parameters were as follows: for thorax and head CT mAs: 100, kV: 80, Beam collimation: 20 mm, CT dose index (CTDIw): 2.84, Pitch: 0.9375, organ tissue weighting factor design: ICRP 103. Simulations of the X-ray source with phantom were also performed for the purpose of validation [17]. The MCNP simulation dose is calibrated to the right dose (per unit integrated tube current) by matching simulated CTDI values with measured CTDI values. The two scanner models used in this study were validated by the approach described in the previous study [17,18].

Results

We calculated maternal and fetal organ doses using MC simulation. When the pregnant female phantom objects RPI-P3, RPI -P6, and RPI-P9 (first trimester, second trimester, third trimester RPI) (Figure 1, 2) underwent thorax CT, the thymus, breast, lung, and heart, which are included in thorax, were showing the highest radiation absorbance followed by liver and esophagus (Table 1). The absorbed fetal total radiation doses were 0.04 mGy, 0.06mGy, and 0.08mGy, respectively. We added shielding of abdomen and got new values of absorbed fetal radiation doses for RPI- P3 pregnant female phantom; these were 0.0048 and 0.0076 after using the lead rubber and antimony-bismuth aprons, respectively. The shielding was very effective, and the lead rubber apron decreased the absorbed fetal radiation dose by approximately ten times (0.04/0.0048=8.39). The lead rubber shielding was more protective than the antimony-bismuth. The visceral organs of female phantom objects due to shieldings absorbed less radiation dose at similar rates (Table 1, 2). The fetal and maternal absorbed radiation doses of RPI - P3, P6, and P9 through head scan were measured (Table 3). The total absorbed fetal radiation doses were 0, 0.01, and 0.01 mGy, respectively.

Table 1. Thorax CT first trimester without shielded dose

Organ/Tissue Name Torax CT(1.trimester)	Without Shielded Doses (mGy)
Fetal skeleton	0.0
Bladder	0.03
Fetal brain	0.04
Fetal soft tissue	0.04
Fetus total	0.04
Ovaries	0.05
Uterine conts	0.06
Brain	0.06
Eyeballs	0.11
Placenta	0.13
Eye lens	0.16
LI conts	0.18
LI wall	0.18
SI wall and conts	0.18
Kidneys	0.44
Pancreas	0.46
Thyroid	0.93
Skin	0.95
Gallbladder	1.07
Adrenals	1.32
Spleen	2.05
Stomach	2.17
Esophagus	2.18
Trachea	2.54
Skeleton	2.68
Liver	2.84
Heart	3.77
Lungs	3.82
Breasts	4.09
Thymus	4.11

Table 2. Torax CT 1st trimester with lead rubber and antimony-bismuth aprons shielded doses

Organ/Tissue Name Torax CT(1.trimester)	0.5 Lead Rubber Aprons Shielded Doses (mGy)	0.5 Antimony-Bismuth Aprons Shieled Doses (mGy)
Fetal skeleton	0.0	0. 0
Bladder	0.0036	0.0057
Fetal brain	0.0048	0.0076
Fetal soft tissue	0.0048	0.0076
Fetus_total	0.0048	0.0076
Ovaries	0.006	0.0095
Uterine_conts	0.0072	0.0114
Placenta	0.0156	0.0247
LI conts	0.0216	0.0342
LI wall	0.0216	0.0342
SI wall and conts	0.0216	0.0342
Kidneys	0.0528	0.0836
Pancreas	0.0552	0.0874
Brain	0.06	0.06
Eyeballs	0.11	0.11
Skin	0.114	0.1805
Gallbladder	0.1284	0.2033
Adrenals	0.1584	0.2508
Eye lens	0.16	0.16
Spleen	0.246	0.3895
Stomach	0.2604	0.4123
Trachea	0.3048	0.4826
Skeleton	0.3216	0.5092
Liver	0.3408	0.5396
Thyroid	0.93	0.93
Esophagus	2.18	2.18
Heart	3.77	3.77
Lungs	3.82	3.82
Breasts	4.09	4.09
Thymus	4.11	4.11

Discussion

During pregnancy, in the evaluation for acute processes such as appendicitis or small-bowel obstruction, or head trauma, the maternal benefit from early and accurate diagnosis may out-weigh the theoretical fetal risks. In cases where magnetic resonance imaging should not be considered as an alternative to CT imaging such as pulmonary embolism, the radiation exposure from CT procedures is inevitable. The CT dose varies depending on kV, mAs, and pitch and can be reduced using a low-exposure technique that is adequate for diagnosis. In the case of suspected pulmonary embolis, CT pulmonary angiogram exposes less radiation to fetus compared with ventilation-perfusion scanning [18]. The effects of prenatal irradiation vary significantly with the age of the offspring. Little is known about what radiation caused during the very early stages between conception and implantation of the human embryo (blastocyst). The effects are best known for the phase of organogenesis (between the 20th and the 50th days postconception). Irradiation with about 100 to 200 rads will incite major developmental anomalies during early pregnancy. In our study, during thorax CT, the absorbed fetal total radiation doses for RPI -P3, RPI-P6, RPI-P9 were 0.04 mGy, 0.06mGy, and 0.08mGy, respectively. In the literature, the anthropomorphic phantom of a woman during early pregnancy showed absorbed fetal radiation dose in the range of 0.02-0.07 for RPI-P3 during thorax CT [19]. Our results are similar to the previous study. However in the literature, for RPI -P6 and RPI P9, there was no reported radiation absorbed dose during thorax CT.

The three phases as implantation, organ primordia, and organogenesis, form about 23% of intra-uterine life. The major teratisms occur after irradiation with about 100-200 rads during organogenesis. In humans, the organogenetic phase ends on the 50th day and is followed by the fetal phase. The critical factor in determining the degree of severity of radiation damage is the correlation between the threshold of irradiation and a given pathological manifestation. There are thresholds for different types of damage, such as the 100 rads level, established as the lowest amount known to produce leukemia in adults. In children irradiated in utero in Hiroshima with doses between 50 and 100 rads, there was a significant degree of microcephaly and mental retardation but no increase in childhood leukemia [20]. Here, the main point to be searched is the doses between 50 to 1 rads level which is applied in diagnostic uses of x-rays.

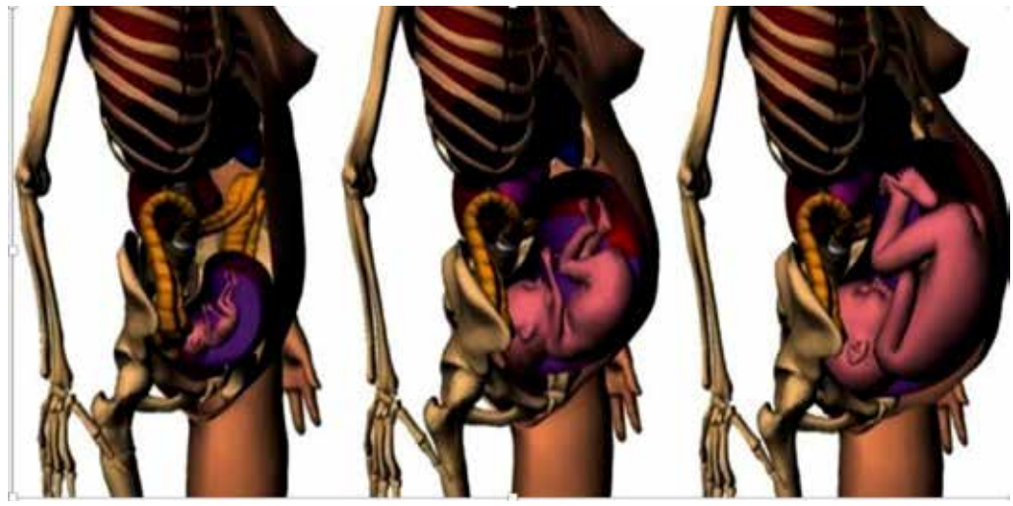

Figure 1. Pregnant phantom model (RPI-P3,RPI-P6,RPI-P9)

In our study, we

Figure 2. The original model of the CT Scanner and RPI of pregnant female phantoms with shielding aprons attached to the table. (General Electric Healthcare Corporation, Waukesha, WI 16 CT with 3D drawing)

Table 3. Cranial CT with/without shielded doses at all trimesters (P3-P6-P9)

	TRIMESTER- CRANIAL CT		
Organ/Tissue Name	**Without Shielded Doses (mGy) FIRST P3—SECOND P6-- THIRD P9**	**0.5 Lead Rubber Aprons Shielded Doses (mGy) FIRST P3--SECOND P6- THIRD P9**	**0.5 Antimony-Bismuth Aprons Shieled Doses (mGy) FIRST P3—SECOND P6 -THIRD P9**
Adrenals	0.01--0.01--0.001	0.0012-0.0012-0.0012	0.0019--0.0019-0.0019
Bladder	0.0--0.0-0.0	0.0--0.0--0.0	0.0---0.0--0. 0
Brain	3.65--3.41--3.21	3.65--3.41--3.21	3.65--3.41--3.21
Breasts	0.06--0.06-- 0.006	0.06--0.06-0.06	0.06--0.06-0.06
Esophagus	0.06--0.06-- 0.06	0.06--0.060.023	0.06--0.06- 0.0026
Eye lens	6.56- 6.18--6.53	6.56--6.18--6.53	6.56--6.18-6.53
Eyeballs	4.94--5.33--5.53	4.94--5.33--5.54	4.94--5.33-5.53
Fetal_brain	0.0--0.0--0.0	0.0--0.00--00	0.0-0.0-0.00
Fetal_skeleton	0.0--0.02--0.02	0.0--0.0024--0.0024	0.0--0.0038--0.0038
Fetal soft tissue	0.0--0.01 --0.01	0.0--0.0012--0.0012	0.0--0. 0019-0.0019
Fetus total	0.0--- 0.01-- 0.01	0.0--0.0012O--0.0	0.0--0.019--0.0019
Gallbladder	0.010--0.01--0.01	0.0-0.0-0.0	0.0019--0.0019-0.0019
Heart	0.05--0.004--0.04	0. 006--0.0048-0.0048	0.0095--0.0076-0.0076
Kidneys	0.01--0.01--0.01	0.0012--0.0012	0.0019--0.0019-0.0019
LI_conts	0.0--0.01 --0.01	0.0012--0.0012-0.0012	0.0019--0.0019
LI_wall	0.01--0.01--0.01	0.0012--0.0012	0.0019--0.0019-0.0019
Liver	0.02--0.02-0.02	0.0024--00.0024--0.0038	0.0038--0.0038-0.0038
Lungs	0.05--0.05-0.05	0. 006--0.005	0.0095--0.05-0.05
Ovaries	0.01--0.00	0.0012--0.0--0.00	0.0019--0.0-0.0
Pancreas	0.01--0.01--0.01	0.0012--0.0012-0.0012	0.0019--0.0019-0.0019
Placenta	0.01--0.03-0.003	0.0012--0.0036-0.0057	0.0019--0.0057--0.0057
SI wallandconts	0.01--0.01--0.001	0.0012--0.0012-0.0012	0.0019--0.0019- 0.0019

applied shielding especially at the three trimesters as RPI P3, P6, P9. The lead rubber shielding was more protective than the antimony-bismuth at all trimesters. The visceral organs of female phantom objects due to shieldings similarly absorbed less radiation dose with similar rates (Table 1, 2).

During head CT, the total absorbed fetal radiation doses for RPI -P3, RPI-P6, RPI-P9 were 0,0.01 and 0.01 mGy, respectively, in the study. There is no literature about MC simulation calculations of pregnant female phantom during the head scan. However, other studies involving fetal dose absorption during pelvic or abdomen region CT scans are seen [17-20].

The chief question is whether this small amount could provoke damage when applied during pregnancy. However, the literature still does not support giving a satisfying response. As a result, protecting the fetus as much as possible, even about the small doses should be our biggest goal. Certainly, all possible ways should be considered to reduce the fetal dose based on the principle of ALARA (as low as reasonably achievable).

Different from other studies, we evaluated the MC calculations of absorbed radiation dose in maternal organs beside fetus and especially in cases of head trauma and pulmonary diseases. In each trimester for each CT scan, the shielding was causing significant differerence. The density of shielding material hence their weights were different where the same thickness bismuth antimony was lighter. In this sense, it would be more practical to use bismuth-antimony apron, we could not commend it would be more protective as much as lead rubber was found.

Scientific Responsibility Statement

The authors declare that they are responsible for the article's scientific content including study design, data collection, analysis and interpretation, writing, some of the main line, or all of the preparation and scientific review of the contents and approval of the final version of the article.

Animal and human rights statement

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. No animal or human studies were carried out by the authors for this article.

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Conflict of interest

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